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PARTICULATE EXHAUST EMISSIONS FROM AN EXPERIMENTAL COMBUSTOR

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16. Abstract

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SUMMARY

The concentration of dry particulates (carbon) in the exhaust of an experimental gas turbine combustor was measured at simulated takeoff operating conditions and correlated with the standard smoke-number measurement. Carbon was determined quantitatively from a sample collected on a fiberglass filter by converting the carbon in the smoke sample to carbon dioxide and then measuring the volume of carbon dioxide formed by gas chromatography. The amount of carbon in the exhaust fell within a range of carbon concentrations previously reported for full-scale engine tests. At a smoke number of 25 (threshold of visibility of the smoke plume for large turbojets) the carbon concentration was 2.8 milligrams of carbon per cubic meter of exhaust gas, which is equivalent to an emission index of 0.17 gram of carbon per kilogram of fuel.

INTRODUCTION

The concentration of dry particulates (carbon) in the exhaust of an experimental turbojet combustor was determined. Because of environmental concerns, standards have been established to limit pollutant emissions from aircraft both on the ground and in low-level flight (ref. 1). Studies such as the Climatic Impact Assessment Program have been made in order to estimate the effect of large fleets of aircraft introducing effluents into the stratosphere (ref. 2). Emissions formed during the combustion process include carbon monoxide, unburned hydrocarbons, oxides of nitrogen, and particulates. Emission levels for the gaseous pollutants are defined in terms of an emission index as grams of pollutants formed per kilogram of fuel burned; particulates are usually indirectly reported on the basis of smoke number. In the smoke number determination a known quantity of exhaust is passed through a fixed area of a specified filter paper, and the reflectivity of the resulting stain is related to smoke number. The smoke number is used primarily as a guide for comparison in determining if the exhaust will be visible for a specific class of engines. A more meaningful value for the concentration of particulates exhausted into the atmosphere would be given by an emission index.

To convert smoke number to an emission index, it is necessary to determine a correlation between smoke number and the carbon concentration in the exhaust gas. (It is assumed that carbon composes the bulk of the dry particulates.) Few investigators have attempted to correlate smoke number and carbon concentration. The correlation of smoke number and carbon concentration reported in reference 3 was obtained by using a processed sample; the large particles were separated from the sample and not included in the carbon determination in order to reduce scatter of the data. In the work of reference 4 an attempt was made to correct the data from reference 3 by compensating for the large particles. The carbon concentrations from reference 3 were considered to be from 0 to 50 percent too low because of the exclusion of the large particles (as had been indicated by unpublished data obtained during the study of ref. 3). In order to establish a range of probable carbon concentration to be expected for a given smoke number, two curves were plotted (ref. 4): (1) the original data from reference 3 and (2) the same data at a level 100 percent higher.

In the present investigation a preliminary study was undertaken in an experimental gas turbine combustor to determine if a correlation between smoke number and carbon concentration could be obtained by using the total particulates collected on a filter. The experimental combustor is described in reference 5. The combustor was operated at pressures of 10×10^5 and 20×10^5 newtons per square meter for each of two inlet-air temperatures, 589 and 700 K, to provide a range of smoke numbers. The smoke number was determined in accord with the specifications set forth in reference 1. The sample for the quantitative determination of carbon was obtained by a procedure similar to that used for the smoke-number determination. The only deviations from the procedure were substitution of finely woven fiberglass filter for the Whatman number 4 filter paper and use of a single sample to obtain the specified weight rather than a number of samples. Carbon was quantitatively determined by converting the carbon on the fiberglass filter to carbon dioxide and analyzing it by a gas chromatography method. Carbon concentration and emission index were correlated with smoke number.

APPARATUS AND PROCEDURE

Test Facility and Combustor

A brief description of the test facility and combustor of reference 5, which were used in this investigation, is presented in the appendix.

Smoke Sample Technique

The exhaust smoke sample was withdrawn through a movable exhaust probe which traversed the combustor exit. In order to obtain a reliable sample for both the smoke-number determination and the quantitative carbon determination, the movable probe was placed in a fixed position for these tests. The sample line was steam heated to maintain the sample temperature above the dew point, and the smoke number was determined with the smoke meter shown in figure 1. The smoke number was determined from the sample collected on a filter paper according to the procedure recommended in reference 1. A range of weight flows was obtained by varying the sampling time while maintaining the standard sample flow rate of 2.36×10^{-4} cubic meter per second (0.50 ft^3/min). The sample weight of exhaust gas per unit of filter spot area W/A was calculated for each of three samples. The smoke number was plotted against W/A on semilogarithmic coordinates with W/A as the logarithmic abscissa. A straight line was fitted through the points by using the method of least squares, and the value of smoke number was determined for a W/A of 1.62 grams per square centimeter (0.023 $lb/in.^2$).

The carbon sample was obtained in a manner similar to that used for the smoke-number determination except that a special filter was substituted for the Whatman number 4 filter specified in reference 1 and only one sample, for an exhaust gas weight flow of 1.62 grams per square centimeter (0.023 $lb/in.^2$), was obtained. The sample area was 3.87 square centimeters (0.6 $in.^2$). The special filter was obtained from the Gelman Instrument Company and is similar to the number 25 filter which can be obtained from Schleicher and Schuell Incorporated. The filter was composed of a finely matted fiberglass and was baked out prior to use. The sample was analyzed by a combustion gas analyzer. The sample was converted to carbon dioxide, and gas chromatography was used to determine the carbon content. A blank was used to correct for any residual carbon not baked out prior to the test. The method is sensitive to the equivalent of 1×10^{-6} gram of carbon.

Test Conditions

The combustor was operated over a range of test conditions based primarily on simulated sea-level takeoff. Pressure, inlet-air temperature, and fuel-air ratio were varied in order to provide a range of smoke numbers. The combustor was operated at inlet pressures of 10×10^5 and 20×10^5 newtons per square meter (150 and 300 psia) for each of two inlet-air temperatures, 589 and 700 K (1060° and 1260° R). Jet A fuel was used, and the fuel-air ratio was varied from 0.01 to 0.02.

RESULTS AND DISCUSSION

The exhaust from an experimental gas turbine combustor was analyzed to obtain smoke number and carbon concentration. In figure 2 the concentration of carbon in the exhaust is plotted against the corresponding smoke numbers for a range of fuel-air ratios and for the four combinations of operating pressures and temperatures. The data are plotted on semilogarithmic coordinates with the ordinate representing the logarithmic carbon concentration expressed as milligrams of carbon per cubic meter of exhaust gas (corrected to standard conditions). The experimental data from the present study fall along a straight line over the range of experimentally determined smoke numbers from 10 to 65, as shown in figure 2. The carbon concentration is 2.8 milligrams per cubic meter for a smoke number of 25, which represents the threshold visibility of the smoke plume from large turbojets.

The data from figure 2 are compared in figure 3 with the carbon concentrations from reference 4. Two curves from reference 4 are shown in figure 3: (1) the lower curve represents the data based on the original study reported in reference 3, in which the large soot particles were separated out, and (2) the upper curve, which is two times the lower curve, represents the maximum carbon concentrations that might have been obtained if all soot particles had been taken into account. The carbon-concentration - smoke-number curves presented in reference 4 were obtained primarily from full-scale J-79 engine tests. The experimental component combustor data of the present study fall within the carbon-concentration range previously determined from full-scale engine testing. At a smoke number of 10 the carbon concentration is 0.86 milligram per cubic meter and is similar to that of the original study of reference 3, in which the large soot particles were eliminated. At a smoke number of 60 the carbon density is 45 milligrams per cubic meter and is similar to that of reference 4, which attempts to account for the large soot particles.

The carbon concentrations from figure 2 are replotted in figure 4 in terms of an emission index. The data are fairly well approximated by a straight line; however, there is more scatter of the data points than in figure 2. The additional scatter is probably due to the use of an average fuel-air ratio in the calculation of the emission index rather than the local fuel-air ratio at the fixed smoke sample probe position. An emission index of 0.17 gram per kilogram is indicated for a smoke number of 25.

A particulate emission index of 0.17 gram per kilogram would correspond to a combustion inefficiency of about 0.013 percent; therefore, as expected, unburned carbon as soot is not an important factor with respect to combustion efficiency. The soot is of importance to the environment, however. It has been estimated that current jet aircraft exhaust emissions of soot particles during cruise are of the order 0.1 gram per kilogram and that soot particle emissions for future engines will be of the order of 0.02 gram per kilogram (ref. 2). Extrapolating the emission-index data of figure 4 indicates that the corresponding smoke numbers would be 17 and 6 for current and future engines, respectively, for cruise conditions.

Also shown in figure 4 is an emission-index estimate based on T-63-A-5A turbojet engine and smoke data from reference 6. The emission index was calculated from an equation based on a curve fit of the carbon-concentration data of reference 3; consequently, for low smoke numbers (less than 30) the engine data should agree fairly well with the experimental emission index, as they do. For engine conditions corresponding to cruise an experimental smoke number of 17 was obtained for the T-63-A-5A turbojet, which is similar to that estimated for current engines in general.

The data from the present study indicate that carbon concentration and smoke number can be related by a rather simple correlation to obtain emission index. Additional data obtained with different full-scale gas turbines as well as a variety of combustor component test configurations would be required, however, before a general expression relating carbon concentration and smoke number could be validated.

SUMMARY OF RESULTS

The particulate exhaust emissions from an experimental gas turbine combustor were analyzed with respect to smoke number, carbon concentration, and emission index. To obtain a range of smoke numbers from 10 to 65 the combustor was operated at pressures of 10×10^5 and 20×10^5 newtons per square meter for each of two inlet-air temperatures, 589 and 700 K, over a range of fuel-air ratios with Jet A fuel. The following results were obtained:

1. The carbon concentrations corresponding to various smoke numbers obtained in the component tests fell within the range of carbon concentrations previously reported for full-scale engine tests. The carbon concentration was 2.8 milligrams of carbon per cubic meter of exhaust gas at a smoke number of 25 (threshold visibility of the smoke plume for large turbojets).

2. The emission index determined from the carbon density was of the order of 0.17 gram of carbon per kilogram of fuel burned for a smoke number of 25.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 11, 1975,
505-03.

APPENDIX - TEST FACILITY AND INSTRUMENTATION

The test combustor was mounted in the closed-duct facility described in reference 5 and shown in figure 5. Tests were conducted at pressures up to 20×10^5 newtons per square meter. Combustion air drawn from the laboratory high-pressure supply system was indirectly heated to 700 K (1260° R) in a counterflow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by being mixed with varying amounts of cold bypassed air. The airflow through the heat exchanger and the bypass flow system and the total pressure of the combustor inlet airflow were regulated by remotely controlled valves.

Combustor instrumentation stations are also shown in figure 5. The inlet-air temperature was measured at station A with eight Chromel-Alumel thermocouples. Inlet total pressures were measured at the same station by four stationary rakes, each consisting of three total-pressure tubes. The total-pressure tubes were connected to differential-pressure strain-gage transducers that were balanced by wall static-pressure taps located at the top and bottom of the duct. Combustor outlet temperatures, pressures, and smoke samples were obtained with a traversing exhaust probe mounted at station B. The probe consisted of 12 elements: five aspirating thermocouples, five total-pressure probes, and two wedge-shaped static-pressure probes. A portion of the aspirated exhaust was bypassed for use as a smoke sample.

The combustor liner used in this investigation was similar to combustor model 3 of reference 5. A schematic of the combustor is shown in figure 6. The combustor had an inlet snout area which was 40 percent of the combustor inlet area. The main portion of the airflow entering the snout passed through air swirlers. A small portion, approximately 6 percent of the total flow, was used to film cool the sides of the combustor. The combustor liner walls were film cooled by means of continuous slots. The dilution air was admitted by means of external scoops. The mass flow distribution in the combustor, also shown in figure 6, was calculated by means of a computer program for the analysis of annular combustors. Fuel was introduced into the combustor through simplex nozzles.

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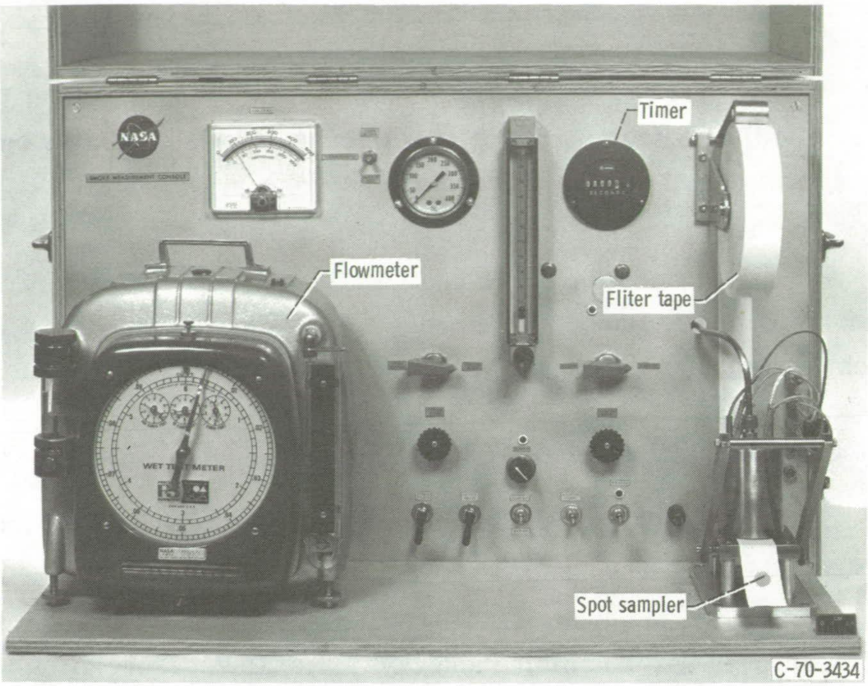
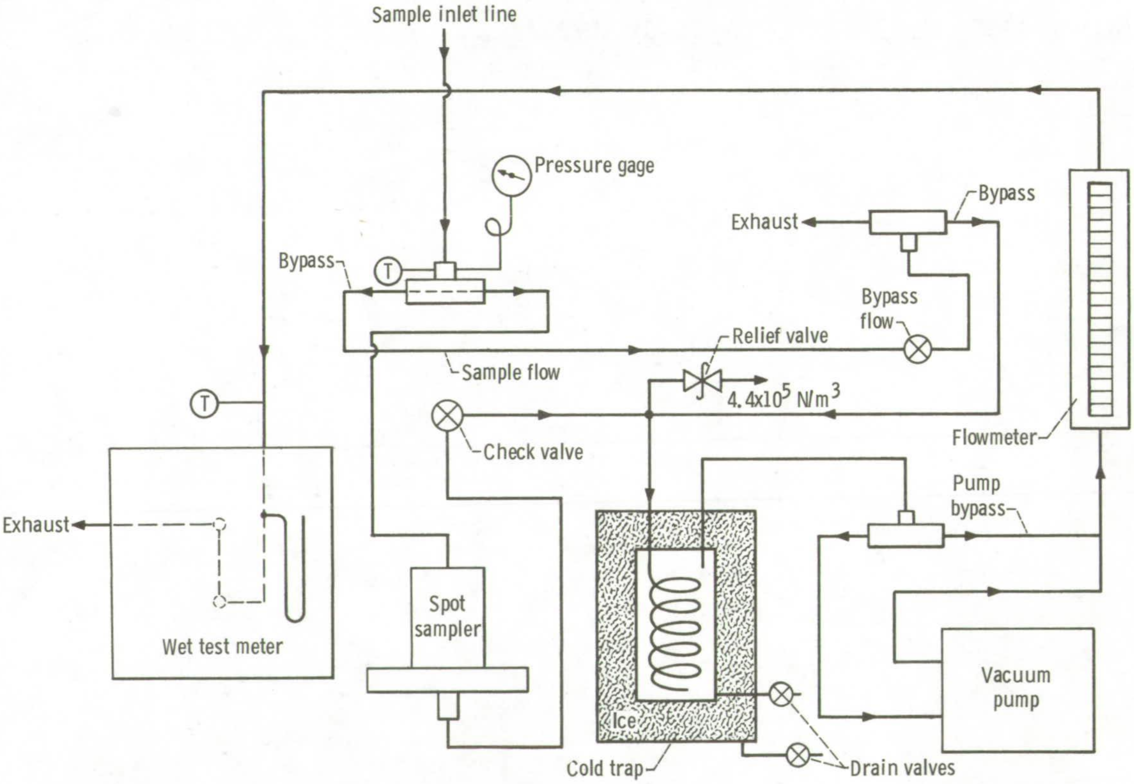


(a) Control panel.



(b) Schematic diagram.

Figure 1. - Smoke meter.

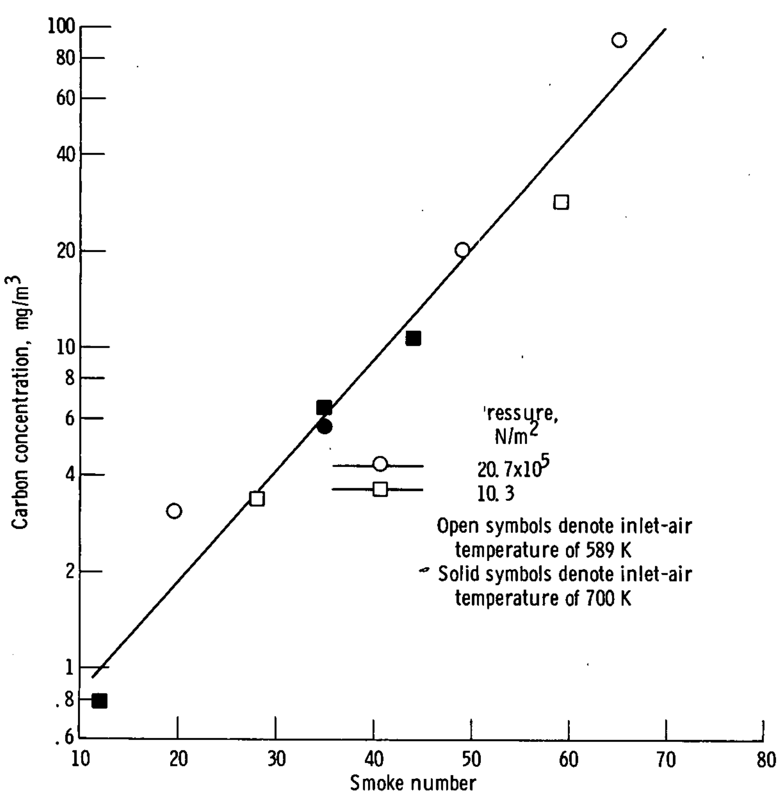


Figure 2. - Correlation of carbon concentration and smoke number obtained from experimental combustor component testing.

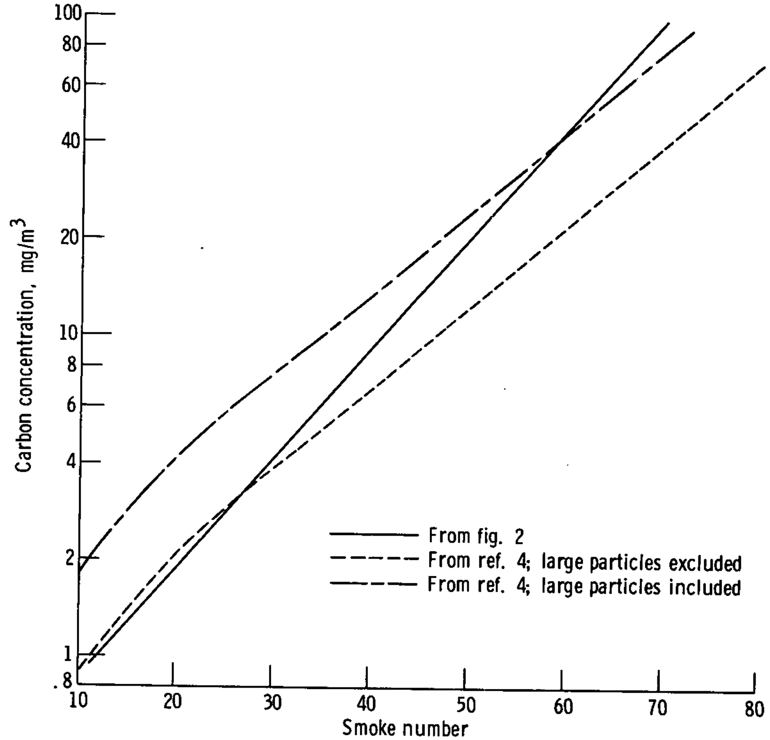


Figure 3. - Comparison of experimentally determined carbon concentration and smoke number with full-scale turbojet engine data.

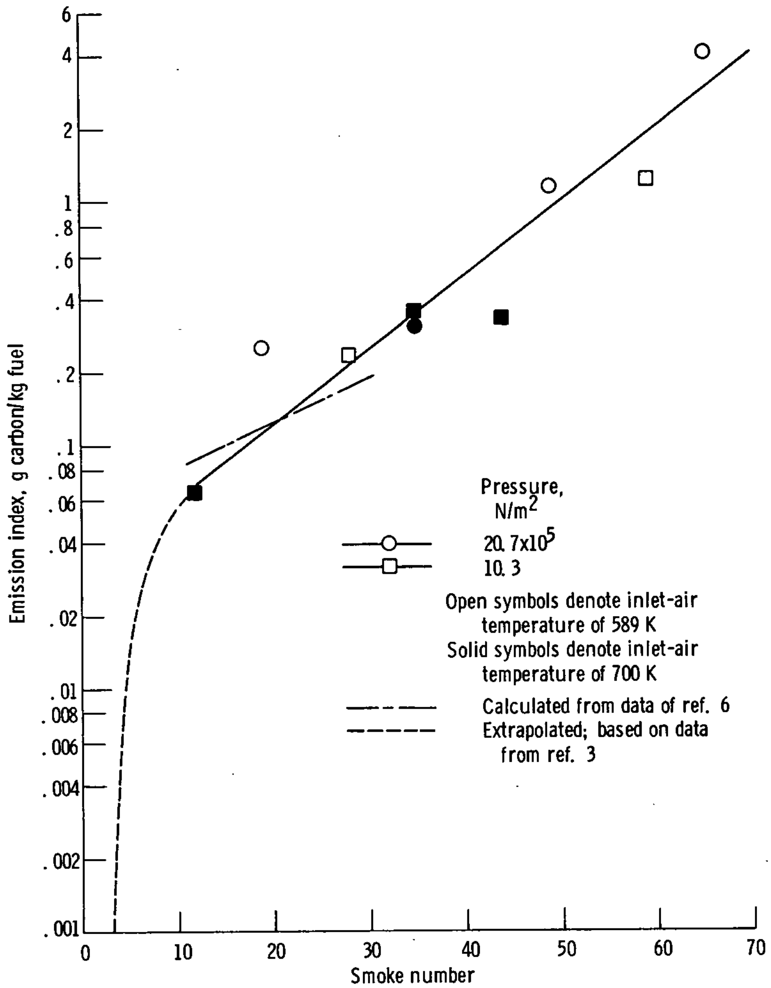


Figure 4. - Emission-index comparison with smoke number.

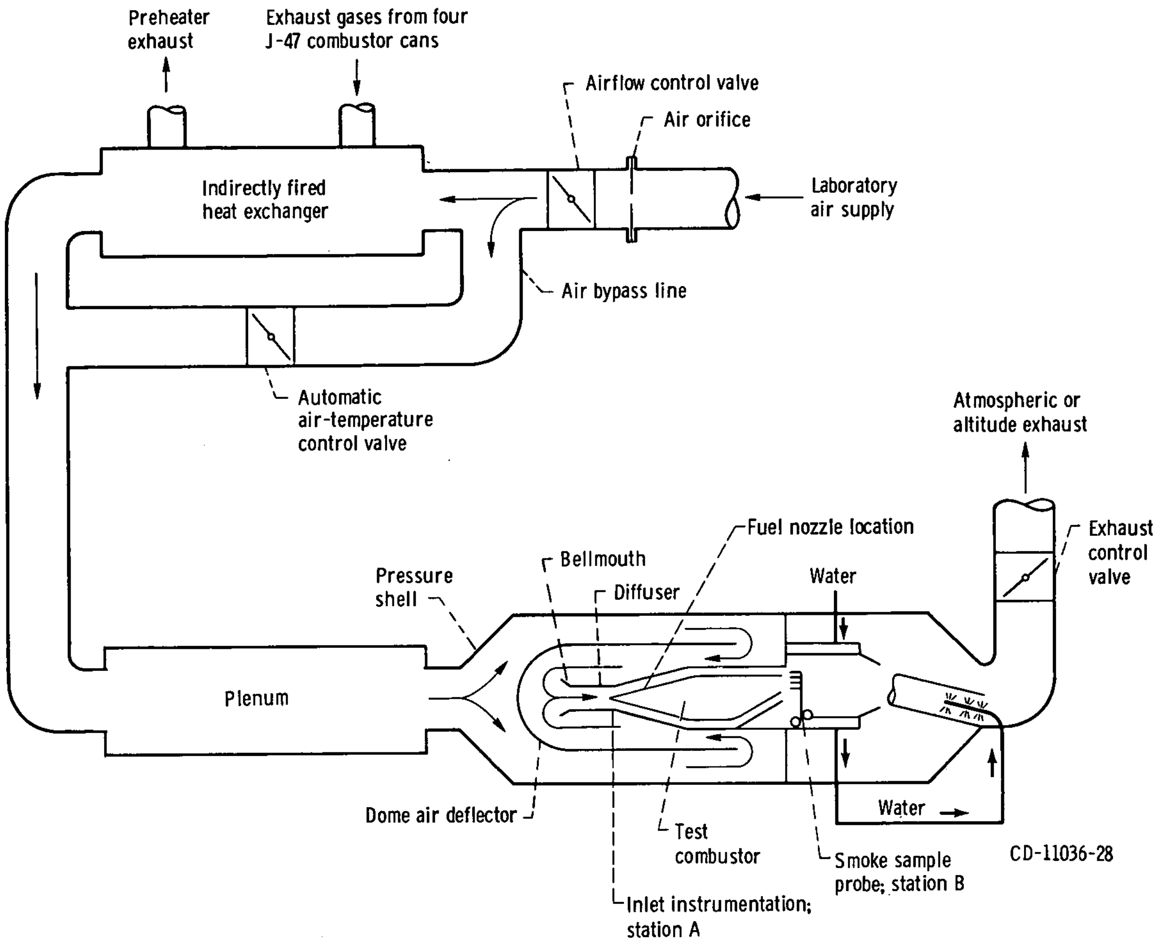


Figure 5. - Test facility and auxiliary equipment.

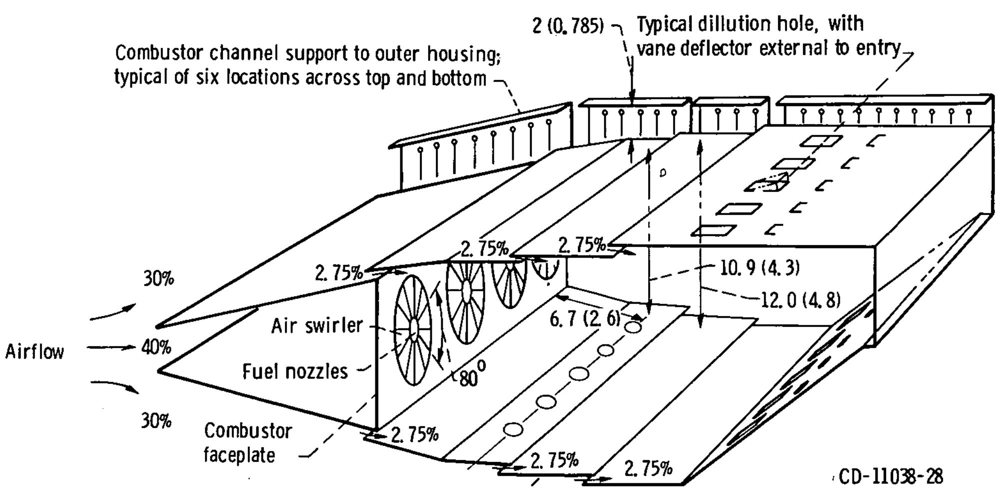


Figure 6. - Schematic of combustor. (Dimensions in centimeters (in.).)

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